Methods for detecting the 3D percolation of photons in the early universe.

Danny Jacobs - Arizona State University
BASP January 2013

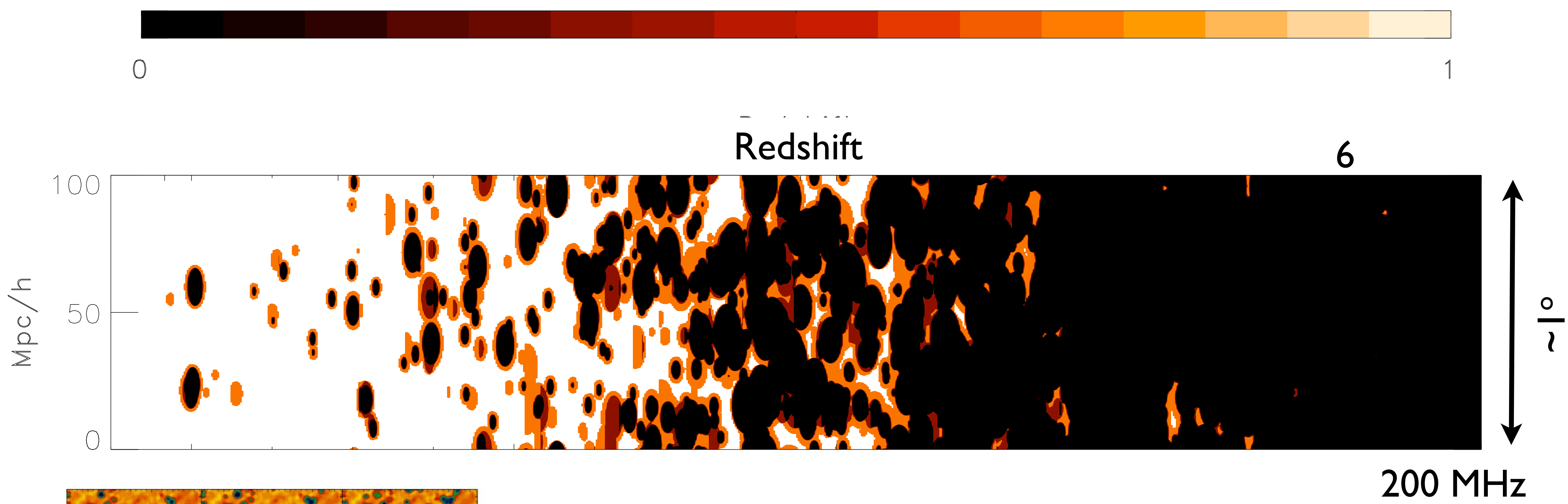
Reionization

LIGHTING UP THE COSMOS

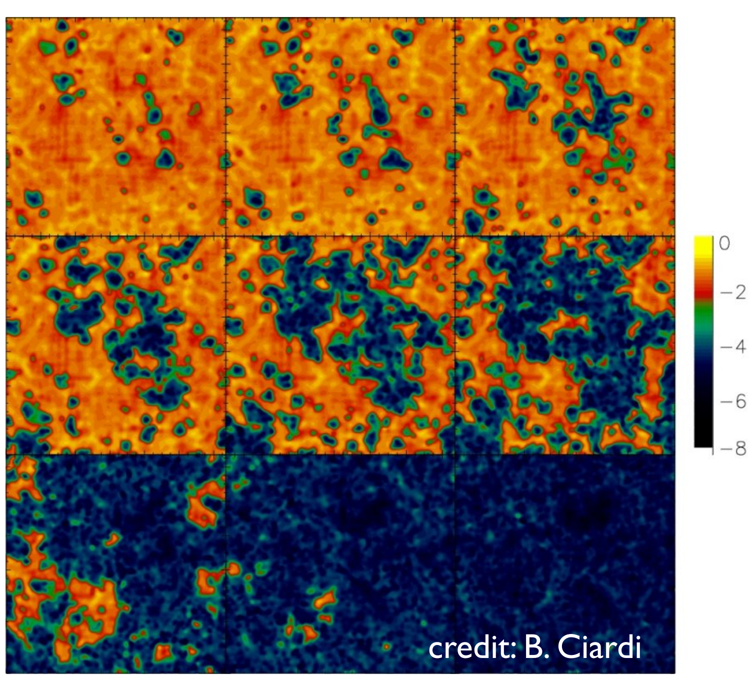
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-years
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters

JEAN-FRANCOIS PODEVIN (*illustration*); STEVEN FURLANETTO, AARON SOKASIAN AND LARS HERNQUIST *Harvard University* (*simulations*)

The Epoch of Reionization



Thomas et al 2009



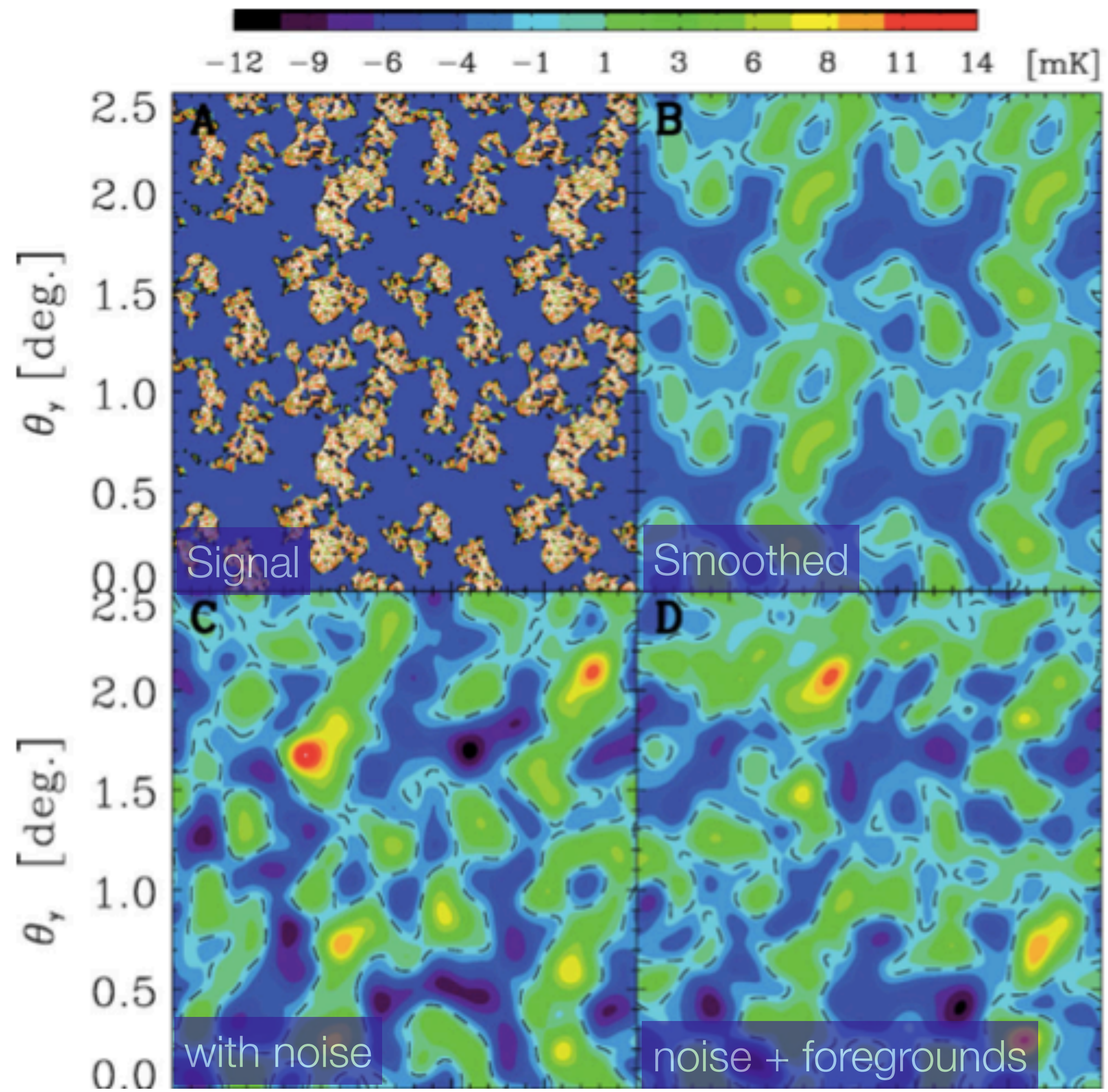
Movies of simulations

M. Alvarez http://www.youtube.com/watch?v=dgXfTx2e2MA

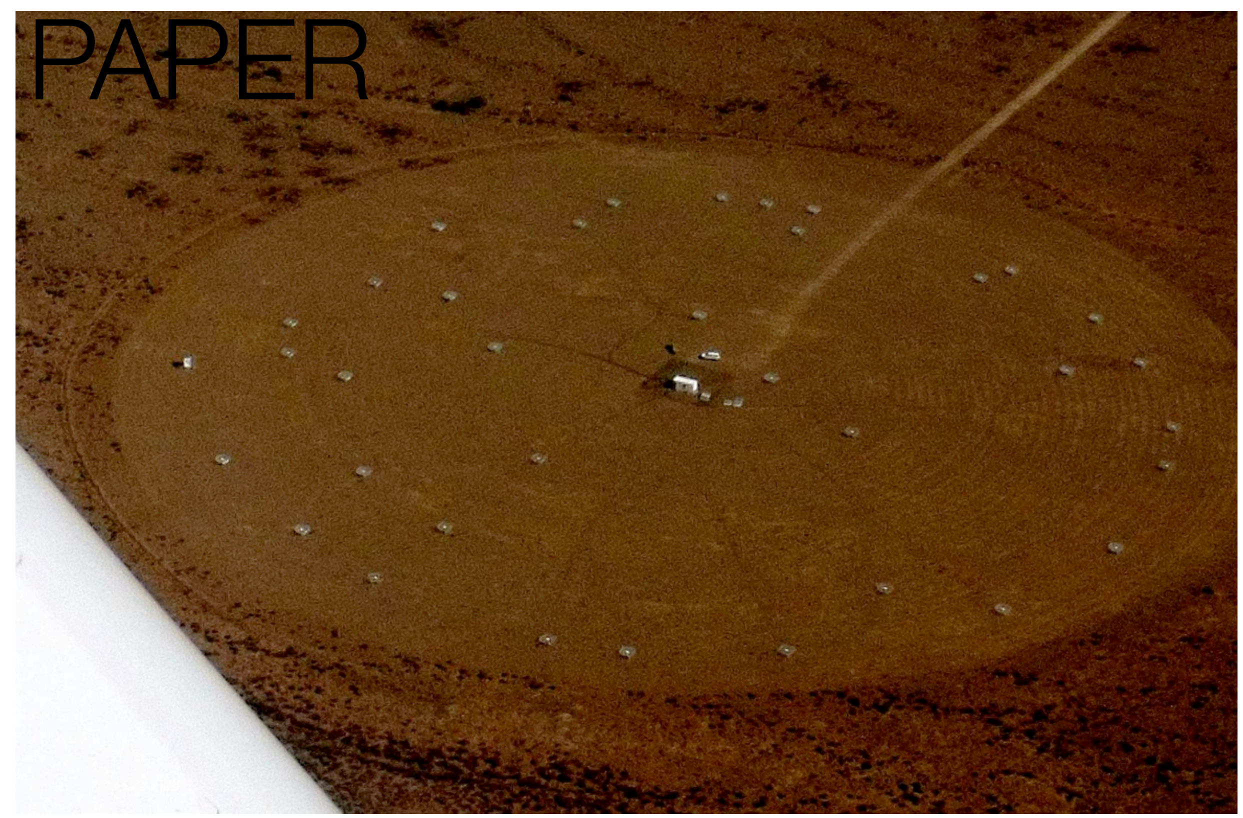
ESO http://www.youtube.com/watch?v=6L1N95IRG8I

Noisy Images

- Typical amplitude: 10-30mK
- Typical noise after deep imaging: 10-30mK
- Statistical detection regime
- Foregrounds are 1000s of K



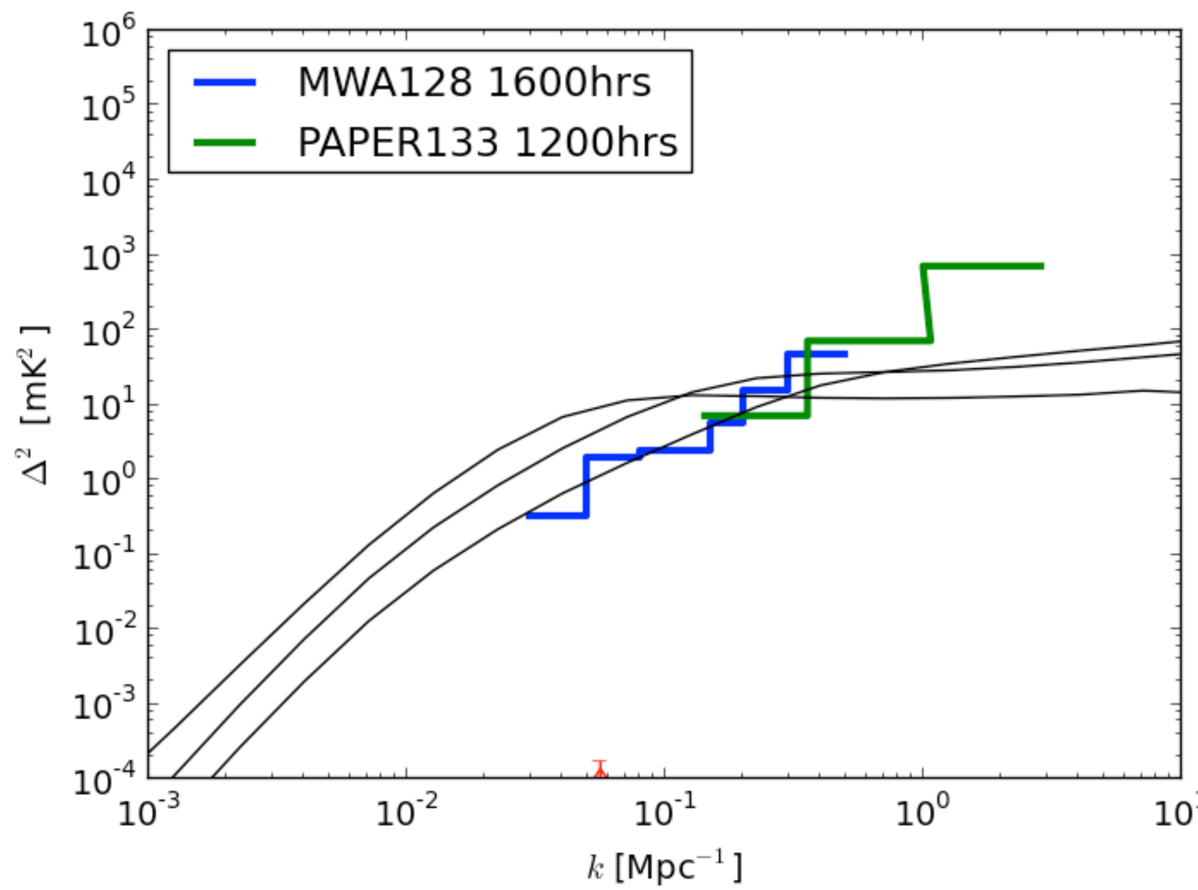
Zaroubi et al 2012



The Murchison Widefield Array (MWA, http://www.mwatelescope.org)
and the Precision Array for Probing the Epoch of Reionization (PAPER, http://eor.berkeley.edu)

Statistical detection

- Power spectrum
- Weiner filtering
- pdf/difference pdf
- bispectrum
- wavelets
- threshold clustering function



Statistical detection

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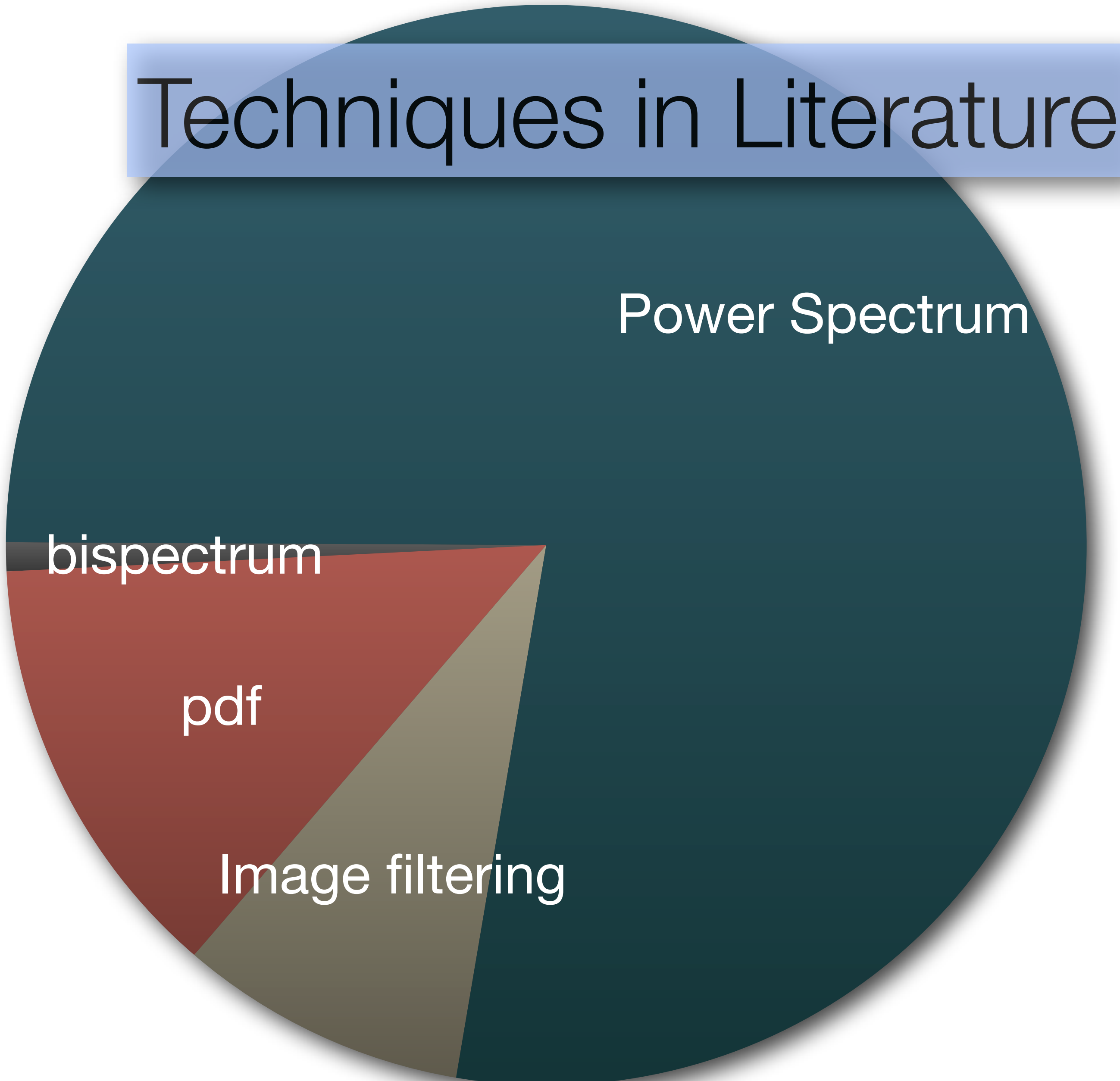

Statistical detection

- **Power spectrum**

- Weiner filtering
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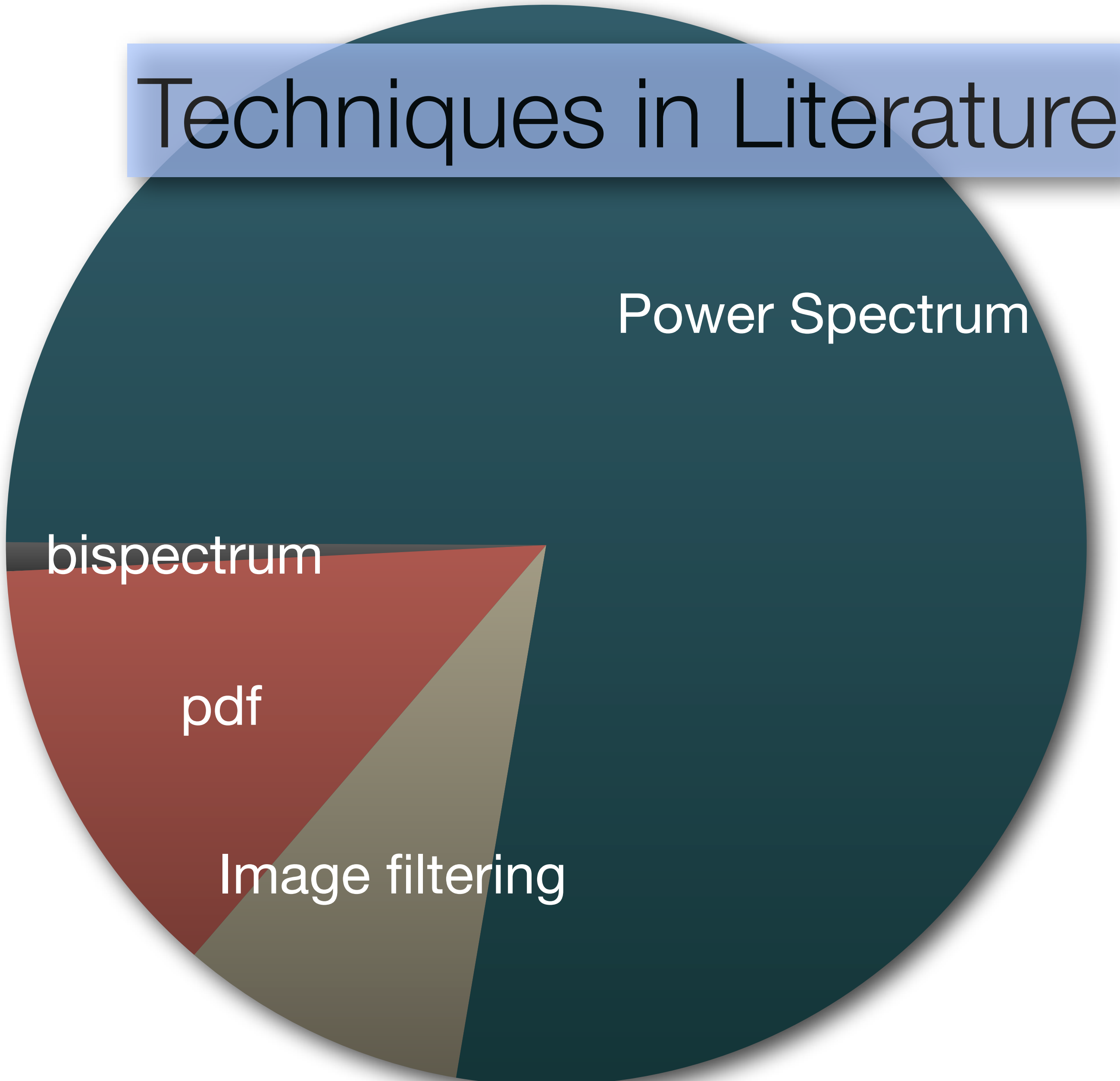
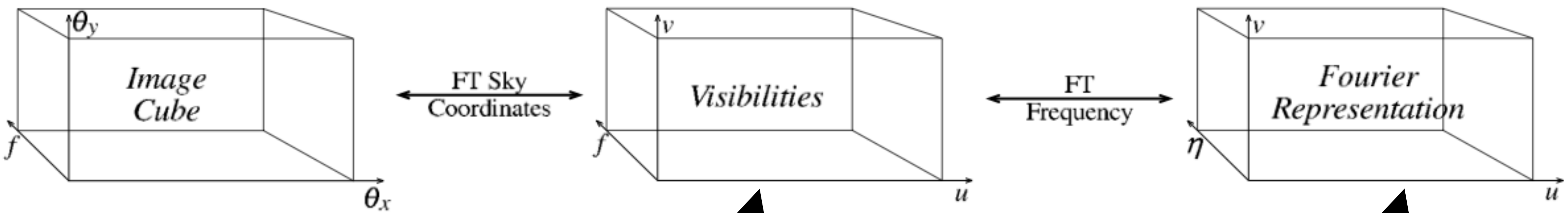
Imaging Required



Interferometry and the Power Spectrum

interferometry measures in Fourier Space

Morales and Hewitt 2004

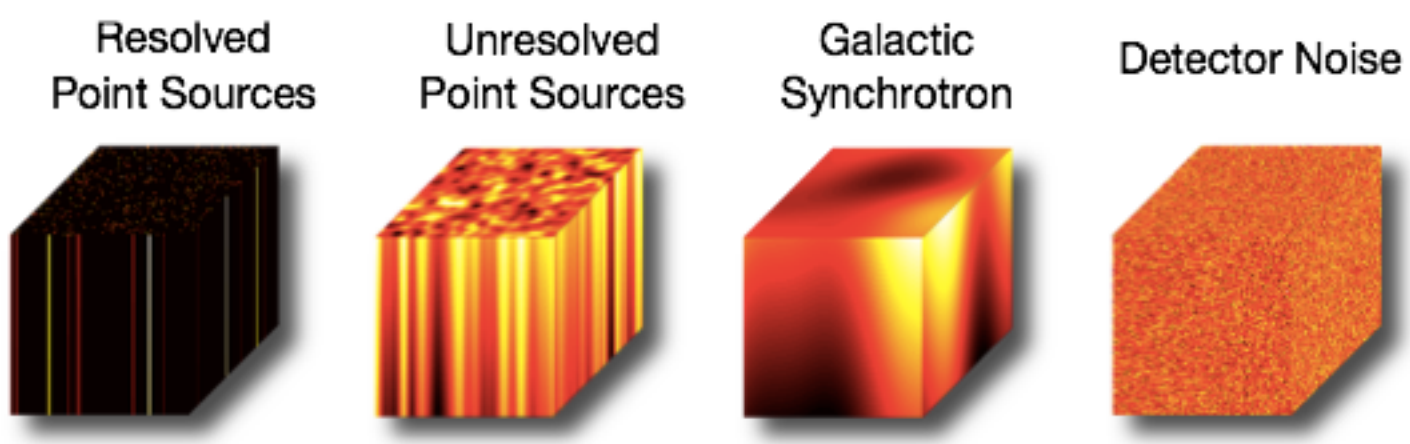


Instrument Frame

Power Spectrum

Foregrounds have smooth spectra

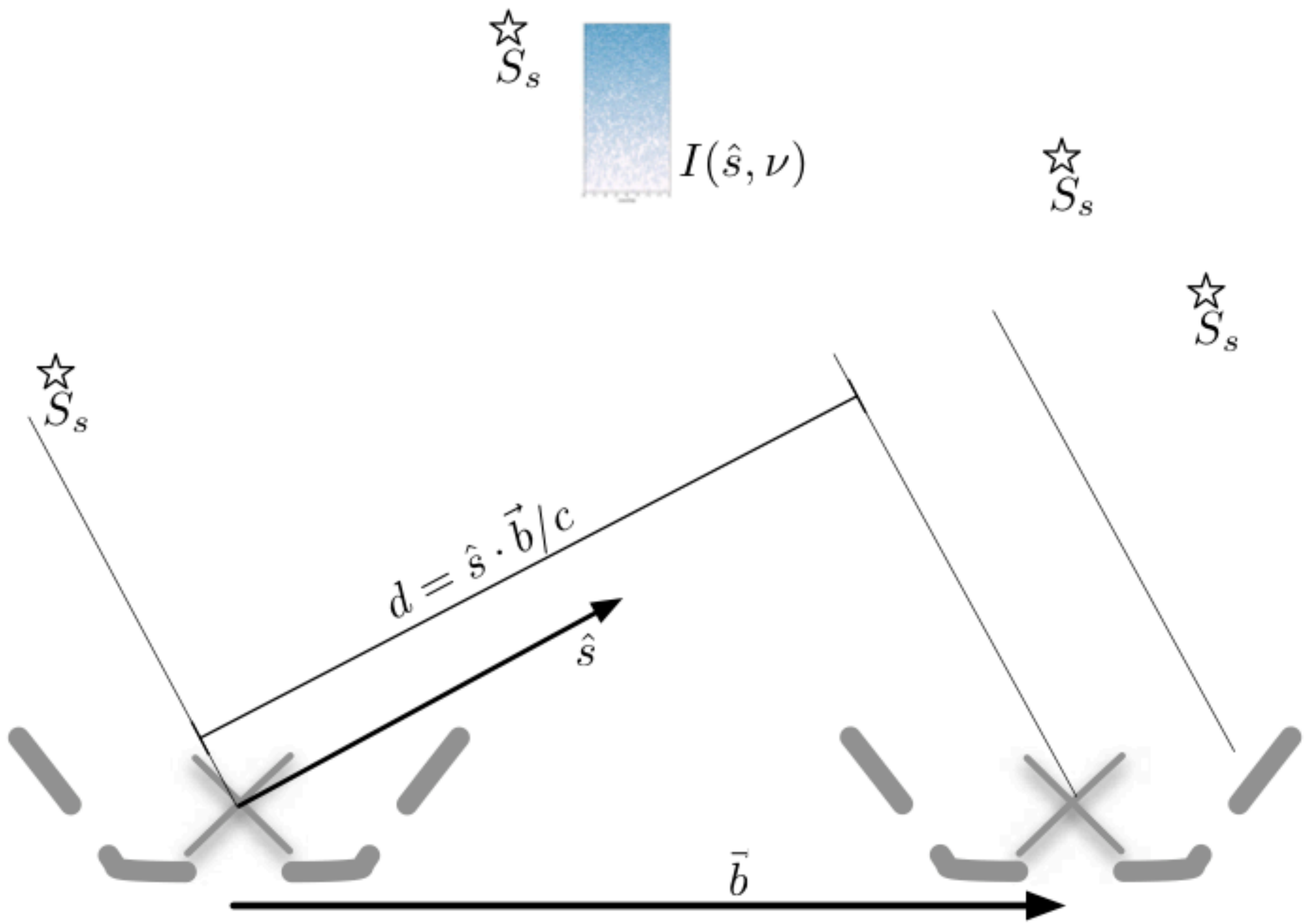
- Foregrounds are spectrally smooth -reionization is not.



Dillon et al 2013

- Much of the foreground is point sources. Which can be simply modeled

Response to Point Sources

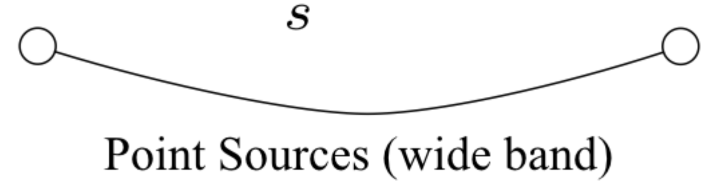


$$V_{ij} \approx \underbrace{\sum_s S_s s^{-2\pi i d_s \nu}}_{\text{Point Sources (wide band)}} + \underbrace{\int I(\hat{s}, \nu) e^{-2\pi i \hat{s}\cdot\vec{b}\nu/c} d\Omega}_{\text{EoR (Narrow band)}}$$

delay spectrum

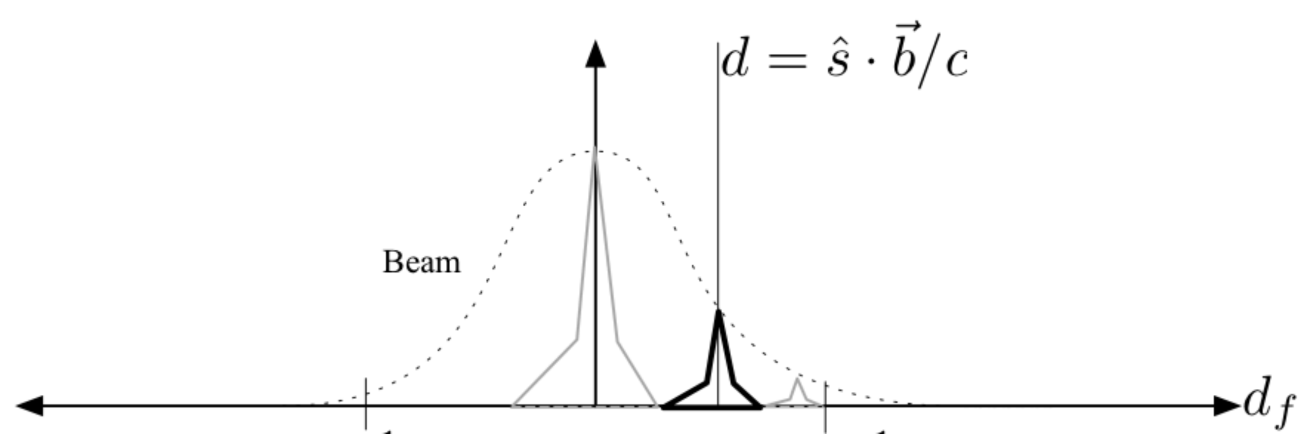
- The interferometer response to point sources

$$V_{ij} \approx \sum_s S_s s^{-2\pi i d_s \nu}$$



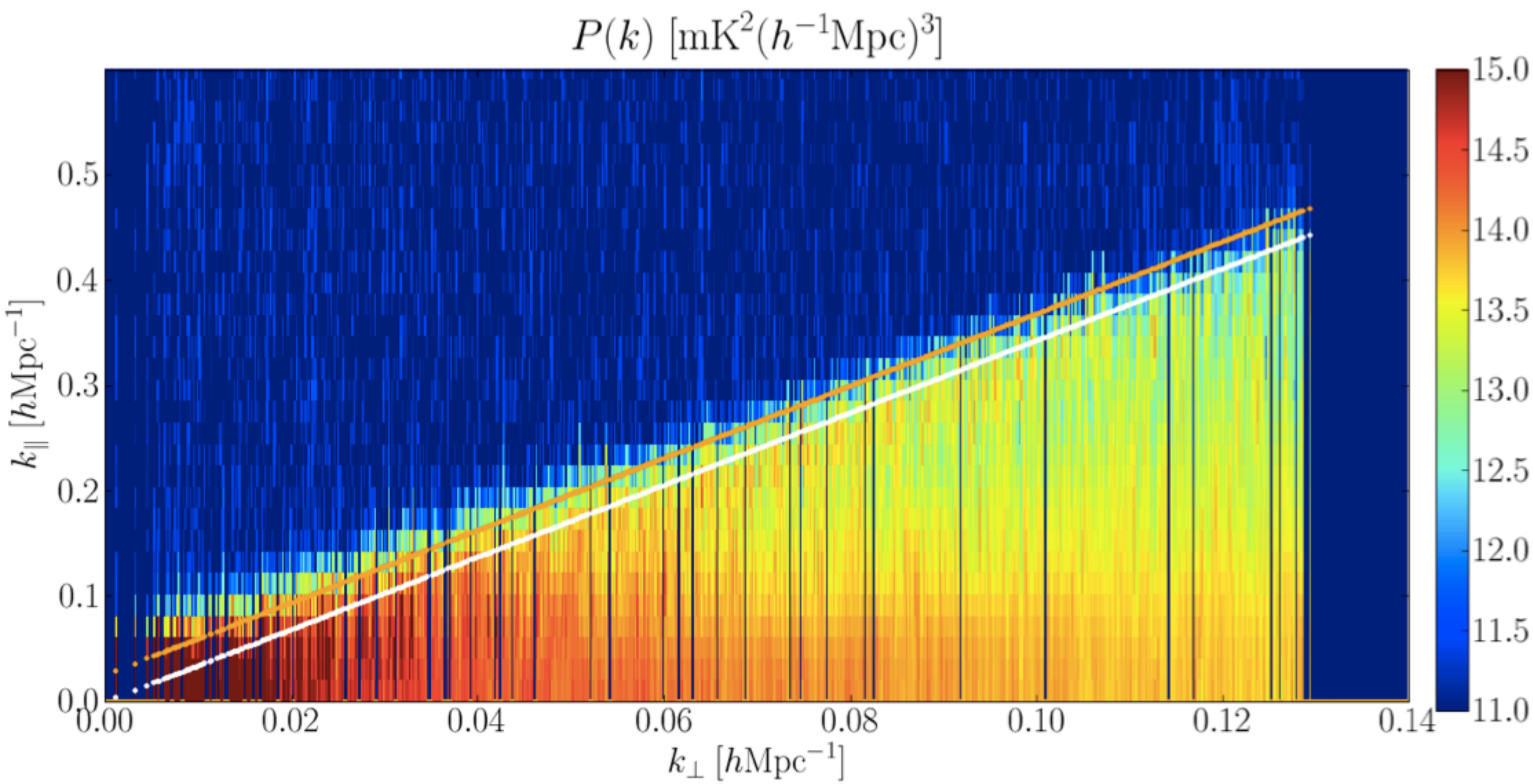
- Is a delta function in the third power spectrum dimension

$$\tilde{V}_{ij} = S\delta(\eta - \hat{s} \cdot \vec{b}/c)$$



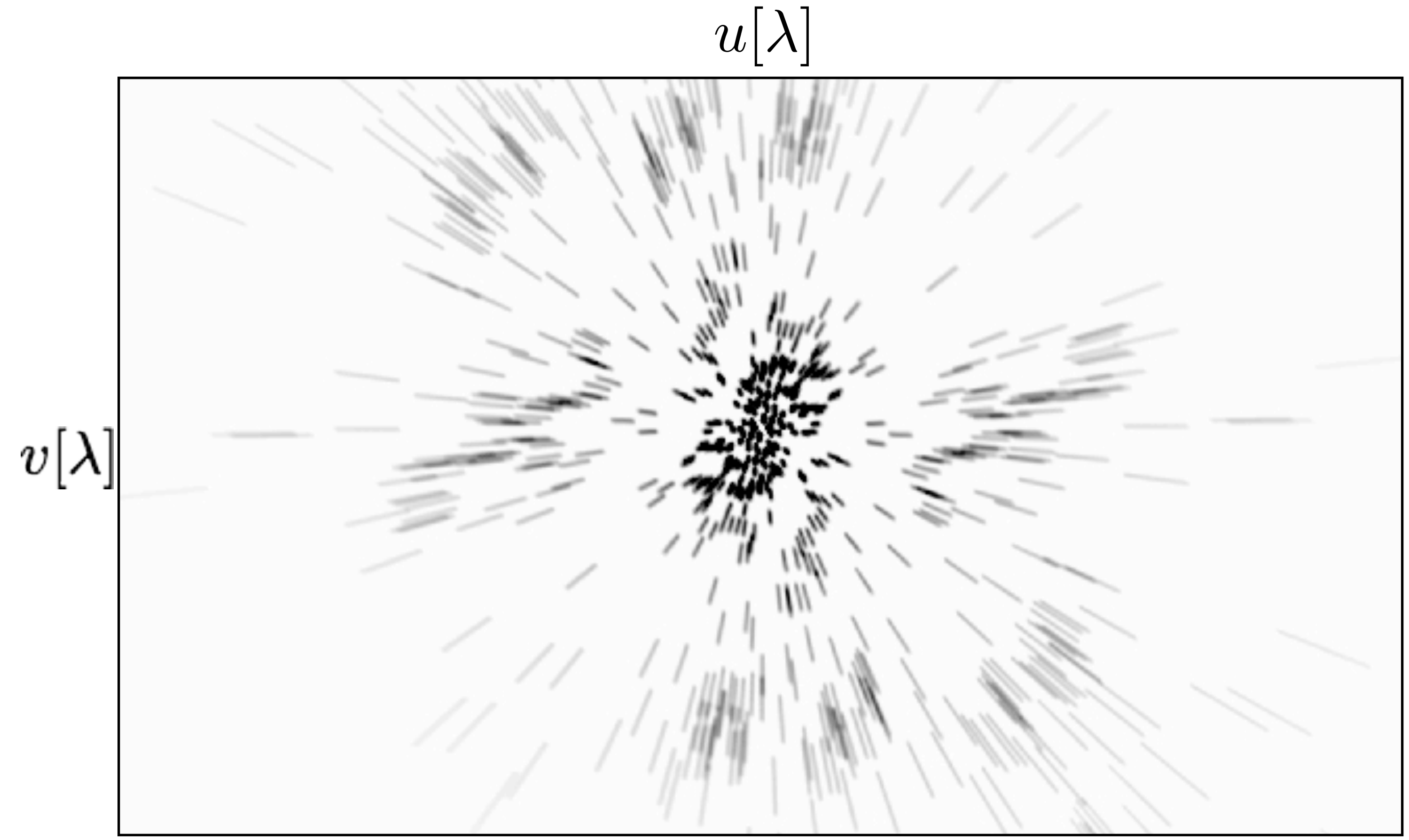
Averaging over many many sources

- Sources limited by primary beam, and ultimately by the horizon
- maximum delay increases with length of baseline.



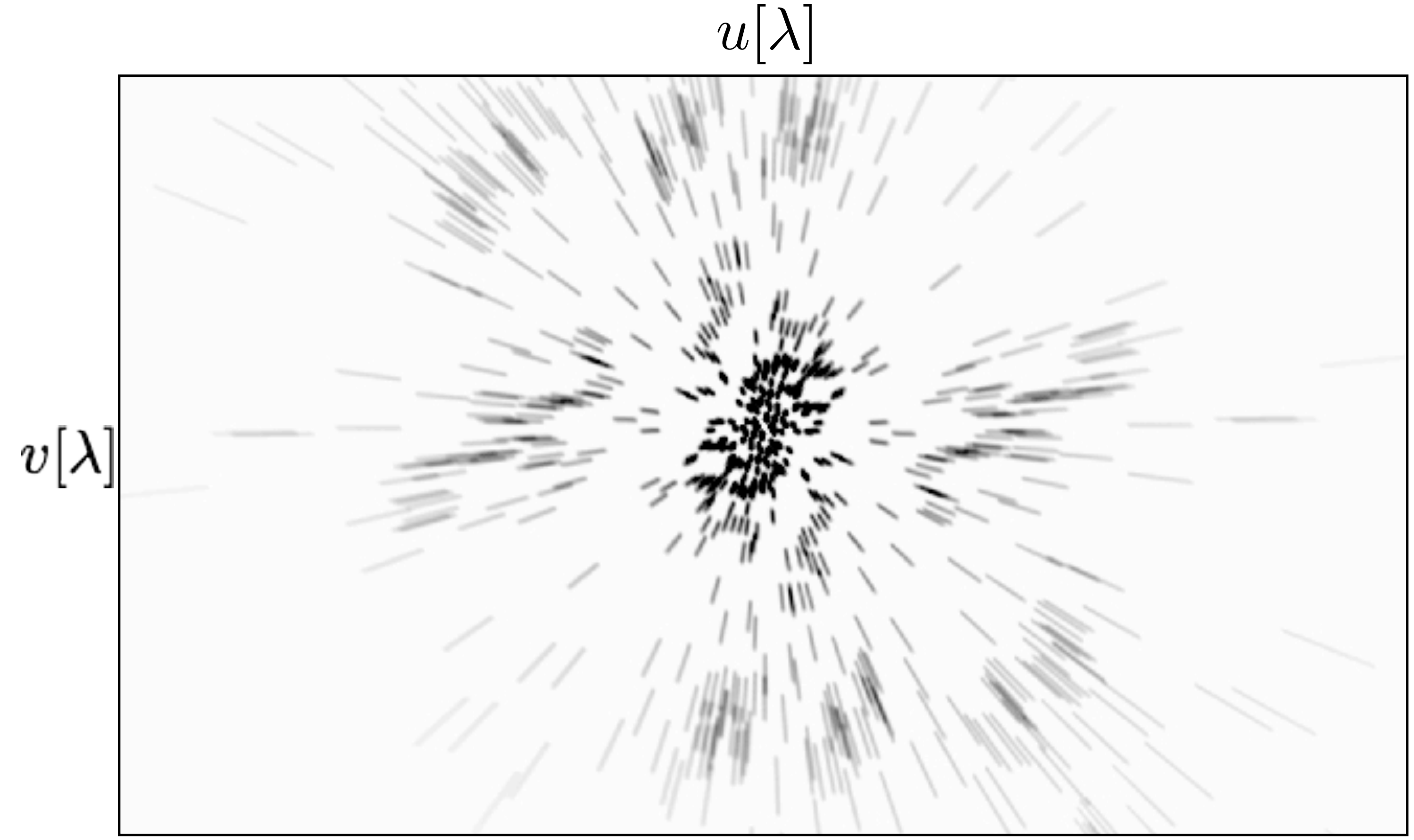
Another Perspective

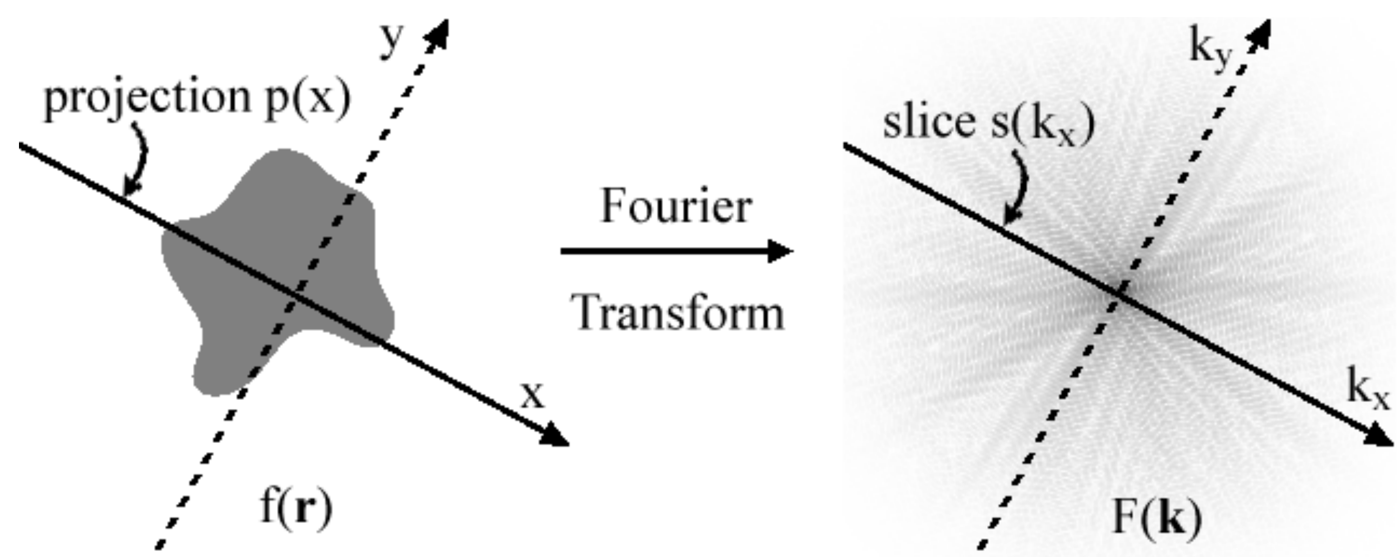
- Each baseline samples the fourier plane.
- Distance from the center of the plane increases radially



Another Perspective

- Each baseline samples the fourier plane.
- Distance from the center of the plane increases radially
- This is also the basic description of the Fourier Slice Theorem
- Each delay transformed baseline spectrum is a projection slice of the sky





Summary of the Reionization Problem as compared to Medical Imaging

- **Separate the data into three components**
    - Foregrounds
    - Noise
    - a bubble and void-like structure
- **Medical Equivalent**
    - Construct a holographic model
    - High noise environment (like ambient field NMR)
    - anomolous structure

Summary

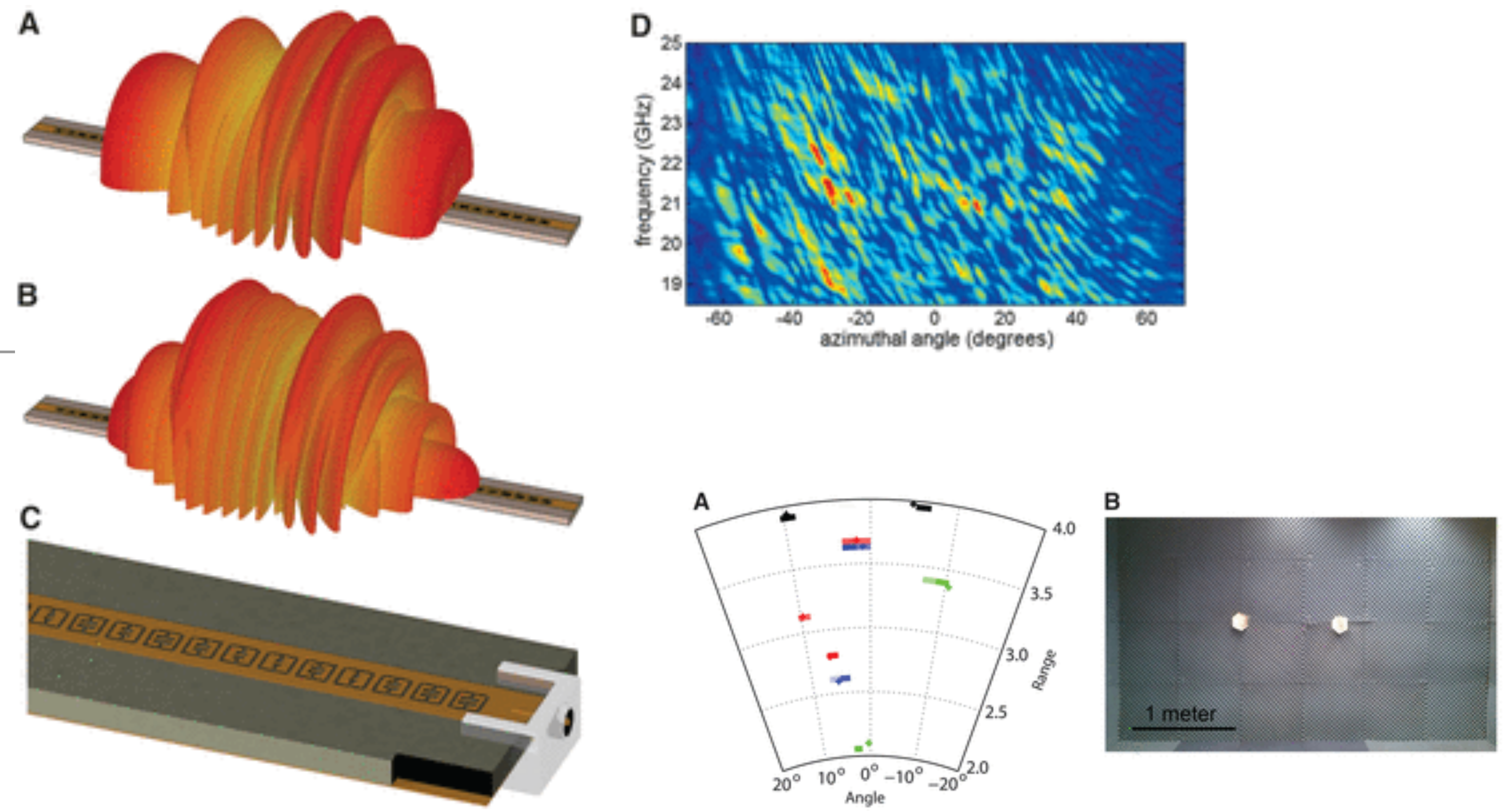
- wide bandwidth correlated spectroscopy of a 3D region
- filter a holographic model of the dominant signal
- Detect anomalous structure in a high noise environment
    - NB: This holography is made possible by the linearity of ElectroMagnetism

Beyond linearity

- the delay transform uses linearity of EM to derive position information

- meta-materials allow the encoding of additional information.

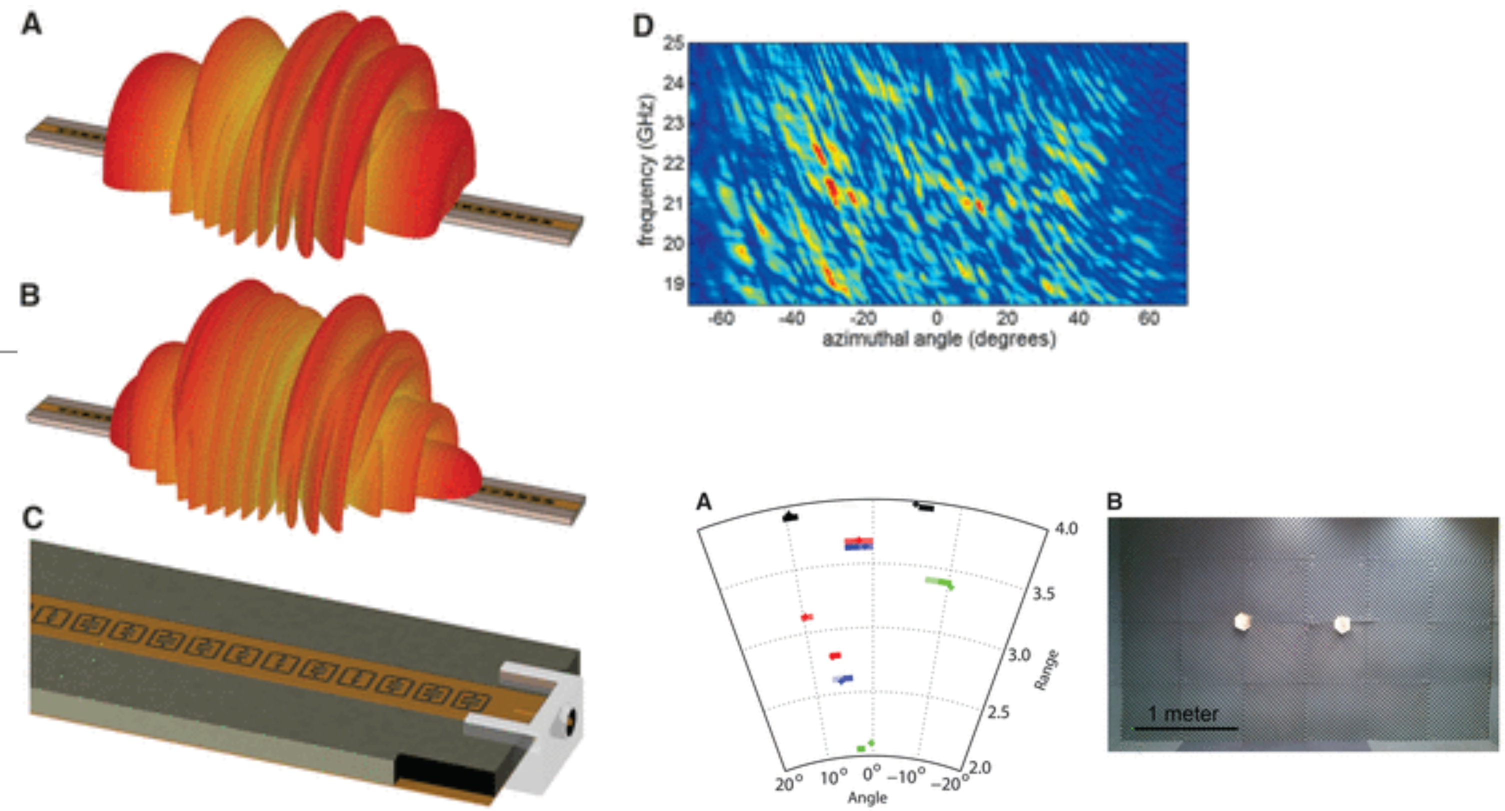
- Scale up this single pixel feed. (20GHz,40cm)



Hunt et al, *Science* (2013)

Beyond linearity

- the delay transform uses linearity of EM to derive position information
- meta-materials allow the selective encoding of additional information.
- Scale up this single pixel feed. (@20GHz - 40cm) (@150MHz-60m)
- One PAPER row = 200m



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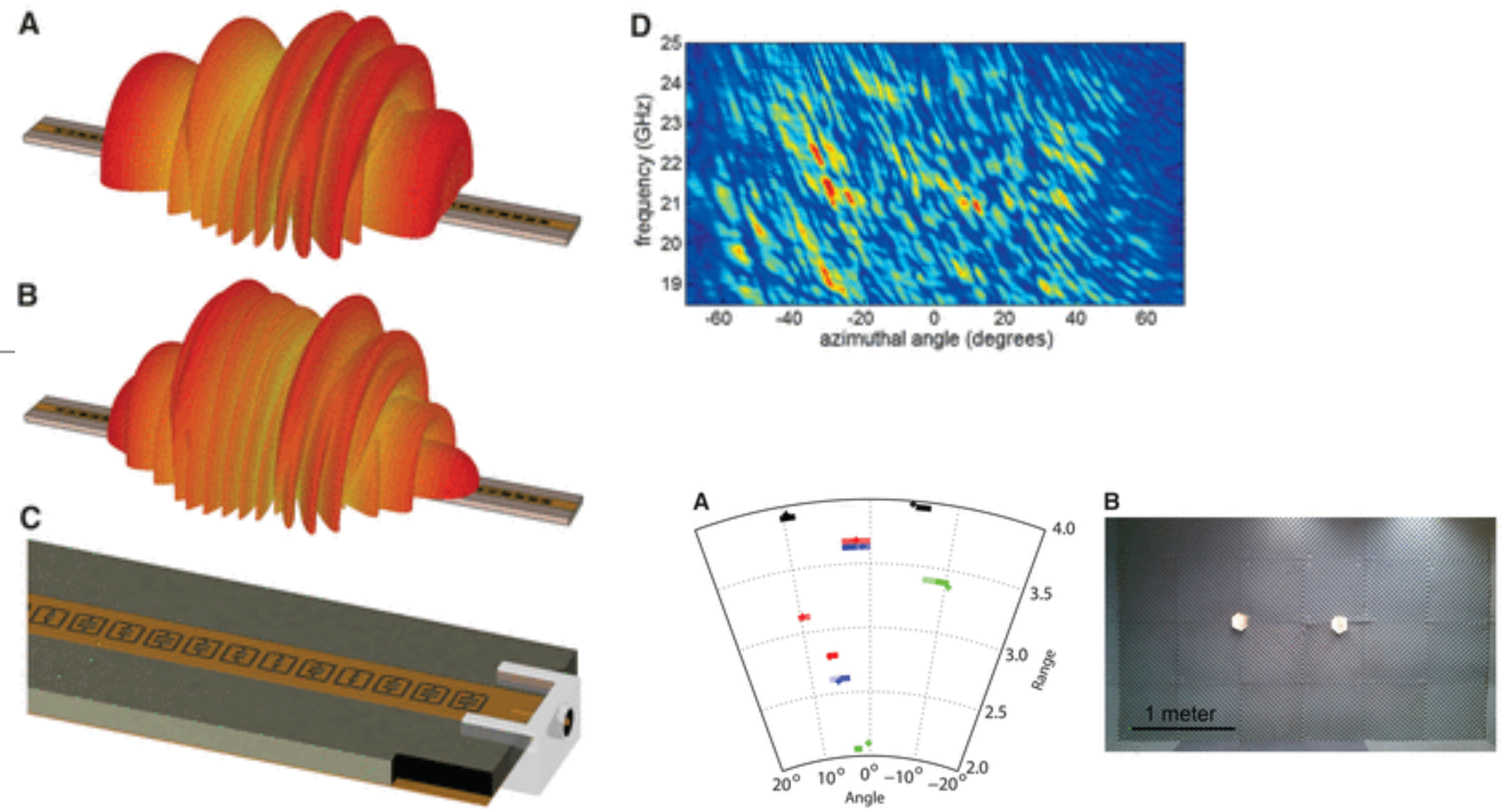
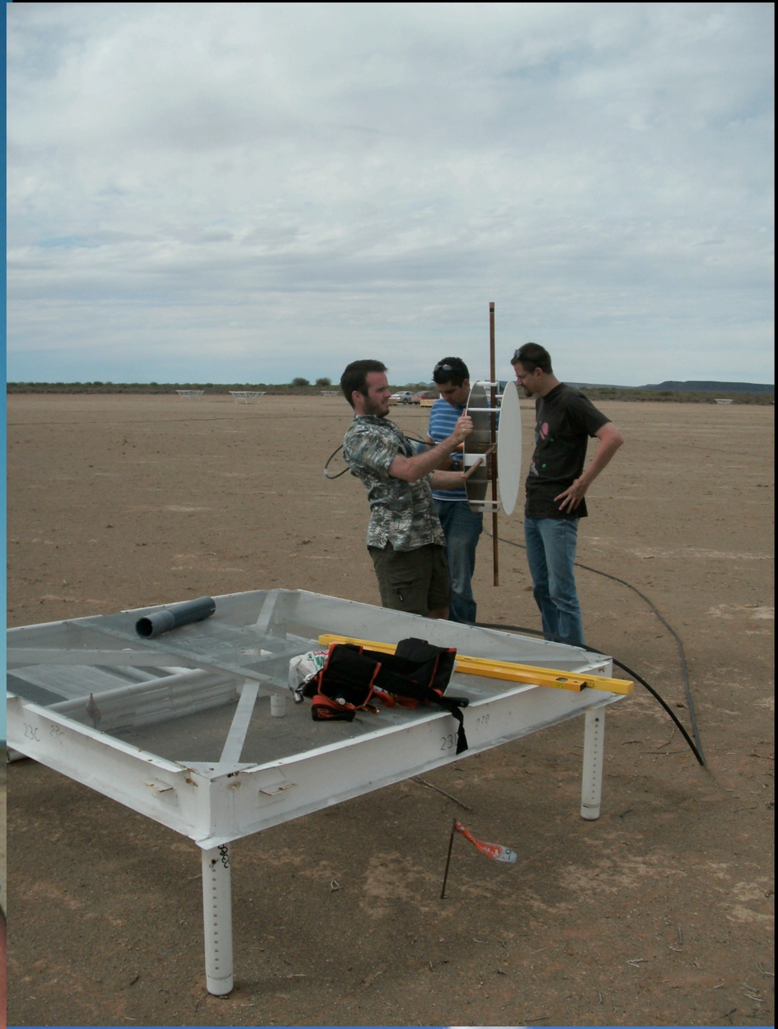


Hunt et al, *Science* (2013)

Some pictures (or The End)

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